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TELEMAMMOGRAPHY USING T1-RATE SATELLITE COMMUNICATIONS

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ABSTRACT
Breast cancer screening through mammography is recommended for tens of millions of American women. Most breast cancer experts, including radiologists who interpret mammography images, reside in large medical facilities, leaving many millions of women far from necessary breast cancer expertise. The coming generation of regional and global satellite networks, providing low-cost T1 rate links, provide a timely opportunity to significantly improve the accessibility of breast cancer expertise, and ultimately the quality of life for millions through satellite-based telemammography. Satellite telemammography also represents a potential market of millions of telemedicine sessions for the satellite service providers. A number of technical and clinical issues which inhibit viable satellite telemammography are currently being addressed by the National Aeronautics and Space Administration (NASA) Lewis Research Center in partnership with the Cleveland Clinic Foundation and the University of Virginia through the Satellite Telemammography Network Experiment using NASA's Advanced Communications Technology Satellite (ACTS), as described in this paper.

BACKGROUND
Breast cancer is the second leading cause of death for American women, with the incidence of breast cancer increasing at a significant rate. However, the disease in 90% curable if detected at an early stage. The primary means of early detection is mammography, an x-ray image of the breast. Studies have shown that mammography can decrease the time to diagnosis of cancer by two years, resulting in a decrease in mortality of 20% to 30%[1]. The growing consensus is that women should receive annual breast cancer screening through mammography beginning at age 40. As of 1996, approximately 56 million American women were within the recommended age group for annual screening. The U.S. Department of Health and Human Services has established the public health policy goal of achieving an annual screening rate of 60% of this population.

Recent trends and legislation have increased certification requirements for mammography. Together with obvious economic and collaborative factors which favor aggregation of specialized expertise, breast cancer experts have become concentrated in large medical facilities, usually in densely populated urban areas. At the same time, more and more mammography screening takes place in small clinics, suburban satellite facilities associated with large medical centers, and even in mobile "mammography vans" which periodically visit remote locations. In many cases, patients must travel large distances to obtain mammography screening.

The primary current method of mammography screening is x-ray filmed based. Screening remotely from the location where the images are interpreted requires physical transportation of the films to the interpretation site. The results are returned several days or even weeks later. The long wait for the screening results creates significant anxiety for the patient. Additional hardships are created for approximately 7% to 10% of patients who must return for additional imaging or other tests when the screening has yielded potential problems or questionable results. These return trips add to the overall cost of mammography screening, and in a significant number of cases, the patient is unable or unwilling to return for additional tests, leading to increased mortality.

The goal of telemammography is to increase the number of patients being screened for breast cancer by decreasing the inconvenience and cost of mammography screening. By electronically transmitting mammography images to the interpretation sites in a rapid fashion, results can be returned during the patient's initial screening visit and necessary additional images or other tests can be obtained without requiring a return trip. Other advantages of telemammography include improved image archiving and retrieval and improved economics for mammography and breast cancer practices and mass screening programs.

Satellites can have a significant role in telemammography because they can fill the gaps in communications infrastructure which occur where terrestrial data communications are unavailable or too expensive. The premise of the Satellite Telemammography Network Experiment being described in this paper is that with some technological advances, T1 rate satellite telemammography will allow high-quality mammography images to be transmitted in a near-real time in order to meet the telemammography goal described above.

The basic concepts of digital mammography and technological and clinical issues for the implementation of satellite telemammography are described in the next sections. Possible implementations of satellite telemammography are given. The Satellite Telemammography Experiment currently underway using NASA's ACTS Satellite will be described and results to date presented. Potential technological advances which will be necessary to make satellite telemammography viable or improve its efficiency will be discussed.

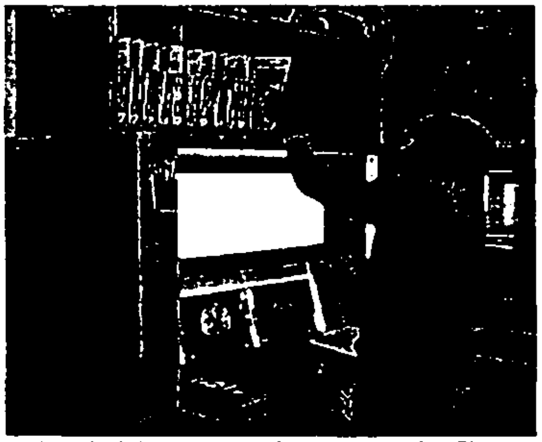
DIGITAL MAMMOGRAPHY

The development of digital mammography will enable many advances in breast cancer screening in addition to enabling telemammography. The current practice of film-based imaging often results in damaged, lost and misfiled films, and transportation, storage, and retrieval difficulties. Digital mammography eliminates these problems and presents other advantages such as image replication without loss of image quality, easy storage and retrieval of images stored in digital archives, the ability to make use of image processing and manipulation techniques to enhance image interpretation, and the eventual use of computer-aided diagnostic algorithms.

Film-based mammography screening is the primary method in use today, and will remain so for the near future. A digital image can be produced from the film using a laser scanner. Direct digital imaging systems are being developed for availability in the very near future, using primarily charge-coupled device (CCD) detectors. Direct digital imaging has the advantage of producing a digital image directly, without the lossy and time-consuming step of laser scanning of film.

DIGITAL IMAGE FILE SIZE AND THE NEED FOR IMAGE COMPRESSION

The most difficult aspect of telemammography lies in the size of the digital mammography image. Although studies of image resolution requirements continue, a consensus is developing that a resolution of at least 50 microns is necessary to resolve important details of mammography, such as microcalcifications, which are direct indicators of cancer. This is a much higher resolution than is required for any other radiology application, and thus makes telemammography the most challenging area of teleradiology. A film laser-scanned at 50 microns can yield a file size of up to 4000 X 5000 X 1.5 bytes, or 30 Mbytes. The direct digital imaging systems produce image files of up to 4000 X 6000 X 2 bytes, or 48 Mbytes.



A technician prepares lmammography films
for light box reading..

Reading of digital mammography images
on high resolution gray scale display monitors.

A typical mammography screening produces two images of each breast (craniocaudal and mediolateral oblique). Often the images from the previous year's screening are also used to look for changes. This results in an overall data transmission requirement of up to 33.2 minutes to transmit 8 images, assuming 100% transmission efficiency, at a T1 transmission rate. Reduction of the image data file size through image compression is essential for "near-real-time" telemammography and the goal of returning mammography screening results during the initial patient visit, as well as to reduce data transmission and archiving costs.

Lossless compression techniques can be applied to reduce the image file size by a factor of about 3 without any loss of image data. The total transmission time at T1 is then reduced to 11 minutes (at 100% efficiency). A study and satellite experiment by General Electric (GE) Corporate Research and Development and Massachusetts General Hospital[2] concluded that lossless compression can result in a transmission time for T1-rate satellite telemammography that will allow results to be returned within the time of a typical patient visit, if a carefully managed "pipeline" approach is followed.

Lossy image compression techniques, which sacrifice some of the original content of the image in return for greatly increased compression rates, can reduce the image file size well beyond the 3:1 ratio achievable with lossless techniques. The difficulty is in determining how much lossless compression can be applied before the diagnostic accuracy of the mammography images is degraded. The image compression must be comfortably below that level. A further difficulty is that the content and density of information in a mammography image varies greatly between patients, so a considerable image compression margin must be maintained.

Wavelet image compression, based on wavelet transforms, is a very promising image compression technique. Studies have indicated that wavelets can achieve compression ratios of at least 30:1 without affecting diagnostic accuracy[3]. Such a compression ratio would reduce the overall transmission time of 8 mammography images to about one minute, even for direct digital images. This would give a considerable time margin for returning screening results to a patient within a typical patient visit time frame compared to the lossless compression case and would save a proportionate cost in transmission and archiving.

A commercial wavelet-based image compression software package, designed for radiology applications, was chosen for study in the Satellite Telemammography Network Experiment. An image compression ratio of approximately 32:1 is used.

DIGITAL IMAGE DISPLAY

The display of digital mammography images remains a challenging issue. Currently the largest gray scale displays capable of presenting radiology images with the necessary luminance are 2K X 2.5K pixel resolution. This is inadequate for displaying an entire 50 micron resolution image, but image manipulation, such as panning, zooming, and leveling can be employed to view the image, and in fact can be exploited to give greater flexibility to mammography readers. There is considerable debate about whether higher resolution displays are needed, or whether only 1K X 1K monitors are adequate. In addition, many digital mammography experts feel that at least two, and perhaps four display monitors are necessary, since interpretation of mammography images involves comparisons between left and right breasts and between current and previous exams. This issue will ultimately be resolved by the mammography community. However, some useful results will occur as a by-product of the Satellite Telemammography Network Experiment.

The workstation design and software required to manage and display digital mammography images are also areas of research at this time. The sheer size and number of images to be manipulated dictates that fast and powerful workstations will be required to create the most efficient mammography workstation. Matching of the film scanners and digital imaging systems with high resolution displays and workstations has not kept pace with rapid improvements in technology. Current studies being performed at the Cleveland Clinic to compare digital with film-based mammography indicate that significant development work is required before a radiologist can interpret a digital mammography exam with even half the speed that a film-based exam allows.

The Satellite Telemammography Network Experiment staff is currently considering several options for the management and display of the mammography images for this effort, including in-house developed software as well as commercial versions of display software.

SATELLITE/TERRESTRIAL INTEROPERABILITY AND PROTOCOL ISSUES

The Digital Imaging and Communications in Medicine (DICOM) 3.0 standard has been developed by the American College of Radiology and the National Electronics Manufacturers Association to enable the communication and transmission of images and other medical information from and between various medical sources and users (computer workstations, MR imagers, film digitizers, archives, etc.)[4]. The DICOM standard is extremely complex (more than 800 pages of documentation), and difficult to apply to telemammography because of the requirement to connect equipment from different vendors. However, it is necessary for mammography images to be DICOM formatted in order to allow mammography images obtained through telemammography to be compatible with a medical center's information network (often called a Picture Archiving and Communications System, PACS).

The DICOM standard operates on top of the transmission control protocol/internet protocol (TCP/IP) communications protocol stack. The TCP/IP protocol includes a cyclic redundancy check for error detection so that data packets received with errors can be retransmitted, resulting in error free data file transmission. However, it presents special problems for satellite links because it was not designed to handle the long time delay which occurs during transmission to and from a geosynchronous satellite. Unmodified TCP/IP operated at T1 data rates over NASA's ACTS satellite resulted in a throughput efficiency of less than 10%, that is, the actual data throughput rate was 150 kbps. This is because the TCP/IP protocol requires the receiver to occasionally send an acknowledgment to the sender, a process which requires two round trips through the satellite with the attendant 0.5 second delay. Modifications of TCP/IP can be employed to improve the efficiency of the transmission. In the GE/ Massachusetts General experiment, DICOM compatible digital mammography images were transmitted over a Ku-Band satellite at T1 data rates using modified TCP/IP and achieved transmission efficiencies of up to 90%[5,6]. A drawback of this TCP/IP modification is that it can be used only for closed networks. In the open internet networks, the modifications violate the TCP/IP standards and will therefore not be recognized. However, a satellite telemammography link can be implemented in a closed network architecture with protocol conversion applied for connections to other networks.

The Satellite Telemammography Experiment will use both the modified TCP/IP protocol and a NASA Lewis in-house satellite/workstation interface which achieves nearly 100% transmission efficiency at the expense of the error free "guarantee" of TCP/IP. Although errors can be detected when using this interface, the entire file must be retransmitted if an error occurs. However, the ACTS satellite has so far provided a high quality link which has not yet required retransmission of an image data set. This indicates that there are possibilities beyond modified TCP/IP for increasing the transmission efficiency of a T1 satellite link for a closed network.

CLINICAL CHALLENGES FOR SATELLITE TELEMAMMOGRAPHY

Two significant challenges for telemammography exist on the clinical side. The first is in the general acceptance of telemammography and the interpretation of mammography images using gray scale displays. Further development of telemammography workstation hardware and software will help to ease the transition from film-based mammography. Development of telemammography session management, including scheduling of patients and radiologists and refinement of the end-to-end telemammography process will help to speed acceptance of the telemammography concept. One goal of the Satellite Telemammography Network Experiment is to identify optimum telemammography processes, and develop and test solutions to bottlenecks which cause inefficiencies in the end-to-end telemammography link.

The second challenge is contained in the need for extensive clinical studies to validate telemammography and prove that diagnostic accuracy can be maintained. In particular, the use of gray scale displays and lossy image compression must be thoroughly studied before acceptance by the medical and insurer communities can be expected. The Satellite Telemammography Network Experiment will create a database of satellite transmitted, compressed digital images to be used in such studies.

SCENARIOS FOR SATELLITE TELEMAMMOGRPAHY NETWORKS

The current telecommunications climate consists of a mixed bag of available services. In some areas, T1, T3, or higher data rate transmission media are readily available. In other areas, cable TV networks have been configured to provide internet-type connectivity at megabit data rates to entire communities, while many remote regions have nothing more than telephone connections. Even within many densely populated areas, high rate telecommunications infrastructure has not been developed and remains too expensive to obtain. Thus, satellite telemammography networks, while ideal for reaching remote patients in sparsely populated areas, may possibly be economical in many other locations as well.

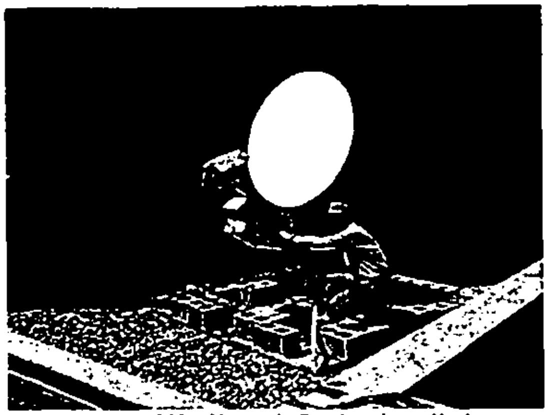
Several scenarios for telemammography networks, supporting various aspects of breast cancer screening and research, can be supported through the inclusion of satellite links. In its basic configuration, a satellite telemammography network would consist of Mammography/Breast Cancer Center of Expertise connected to a number of remote sites at which breast cancer screening is performed. The use of satellite links means that there is theoretically no limit on the distance between the Center of Expertise and the remote screening sites. They can be located in suburban areas surrounding major metropolitan areas as well as very remote, rural locations, reaching small towns or mobile mammography vans. By making use of T1 rate connections, the basic image transmission and remote diagnosis can be augmented by teleconference capabilities which can provide teleconsultation between remote physicians or directly between patient and physician.

The basic satellite telemammography network model can be expanded to include more than one medical center in order to create a distributed mammography group practice, to allow for multiple readings of mammography screening, and to generally increase the pool of available mammography readers, as well as provide expanded breast cancer expertise for consultation and second opinions. Satellite telemammography networks would also allow the development of regional archives for mammography images and breast cancer data. This would allow the tracking of regional trends and provide a data base for breast cancer research.

THE SATELLITE TELEMAMMOGRAPHY NETWORK EXPERIMENT

The Satellite Telemammography Network Experiment is a joint effort by the NASA Lewis Research Center, the University of Virginia, and the Cleveland Clinic Foundation. The goal of the experiment is to develop and demonstrate technologies and methods that will allow the delivery of high quality, high resolution mammography images using low cost, high access T1-rate regional and global satellite networks.

NASA's experimental ACTS Satellite will be used for the experiment. Launched in 1993, ACTS has demonstrated advanced satellite communications technologies including on-board switching and processing, hopping multi-spot beam antennas, and Ka-band links. ACTS has provided experiment opportunities for a variety of applications, including telemedicine, using data rates from 2.4 kbps to 622 Mbps[7]. Of particular usefulness to NASA's satellite telemammography effort is the ACTS T1-VSAT (Very Small Aperture Terminal) network. This advanced, time-division multiple access network uses an on-board baseband processor to switch between geographically distributed users accessed by small satellite antenna spot beams. The narrow, high gain spot beams allow T1-VSAT terminals to have antenna dish diameters of only 1.2 meters. The on-board processing also allows forward error correction to be applied to either the uplink or downlink in order to maintain a high link quality in the event of signal fade caused by rain or other disturbances at either end of the link[8]. Thus, the ACTS T1 VSAT network functionally represents the



ACTS T1-VSAT Earth Station installed
at the University of Vriginia

capabilities of proposed future regional and global Ka-band satellite networks which will offer relatively low-cost, on-demand T1 rate connectivity, and is therefore an excellent testbed for satellite telemammography.

The basic configuration of the Satellite Telemammography Network Experiment is shown in Figure 1. Three T1-VSAT Earth Stations are dedicated to the three experiment participants. Earth Station #2 is the NASA Lewis station, and in most of the planned experiments NASA Lewis will simulate a remote mammography screening site which has produced digitized mammography images for distribution to one or the other mammography centers of expertise. Earth Station #2 is located at NASA Lewis and is connected to the telemammography lab in an adjacent building through an internal T1 transmission line.

Earth Station #1 is dedicated to the Cleveland Clinic, but is also located at NASA Lewis. It is connected to the Cleveland Clinic campus through a commercial T1 circuit, a connection of about 20 km in length. At the Cleveland Clinic Education Building, the T1 line terminates at a transfer workstation, which is connected to the Cleveland Clinic internal campus 10 Mbps PACS local area network. Using this network, images are transmitted to the telemammography workstation in the Radiology Department, several buildings away, for display and diagnosis. Thus, the Cleveland Clinic connection represents a true hybrid satellite/terrestrial link, containing the satellite link, a commercial terrestrial T1 line, and a local area data network.

Earth Station #8 is located at the MR-4 building of the University of Virginia's Health Sciences Center on the roof above the laboratory where the telemammography experiments take place. This node of the satellite telemammography network is directly connected to the satellite earth station.

There are three parts of the Satellite Telemammography Network Experiment plan. The first part, currently underway at the time of preparation of this paper, consists of the following: developing, debugging, and testing the physical network; testing the transmission of images under both TCP/IP and the NASA protocol described earlier; determining the impact of the satellite link including rain effects; and developing and testing the hardware and software required to simulate an end-to-end telemammography session.

The second part of the experiment plan consists of testing the effectiveness of the end-to-end satellite telemammography process. This includes varying elements of the process, such as the image compression ratio, to determine optimum methods and identify process bottlenecks. Some simulated telemammography sessions will include radiologists who will interpret received mammography images at the mammography expert centers and report back the diagnostic results. Other sessions will include transmission to both expert sites to simulate multiple reading and consultation processes.

The third part of the experiment consists of processing (applying image compression to DICOM image files) and transmitting carefully selected mammography cases to the University of Virginia and Cleveland Clinic sites. The received, compressed image files will be stored for later use in clinical studies which will determine if diagnostic accuracy can be maintained in satellite telemammography with lossy image compression.

EXPERIMENT RESULTS

Earth Stations #1 and #2 and the terrestrial connection to the Cleveland Clinic became operational in March, 1997. Two months were spent testing interfaces, both hardware and software, and developing some processes for mammography image transmission. Development of hardware and software for image display has taken place during this time and is continuing. Earth Station #8 became operational at the University of Virginia in early June, 1997, and is currently undergoing debugging and testing.

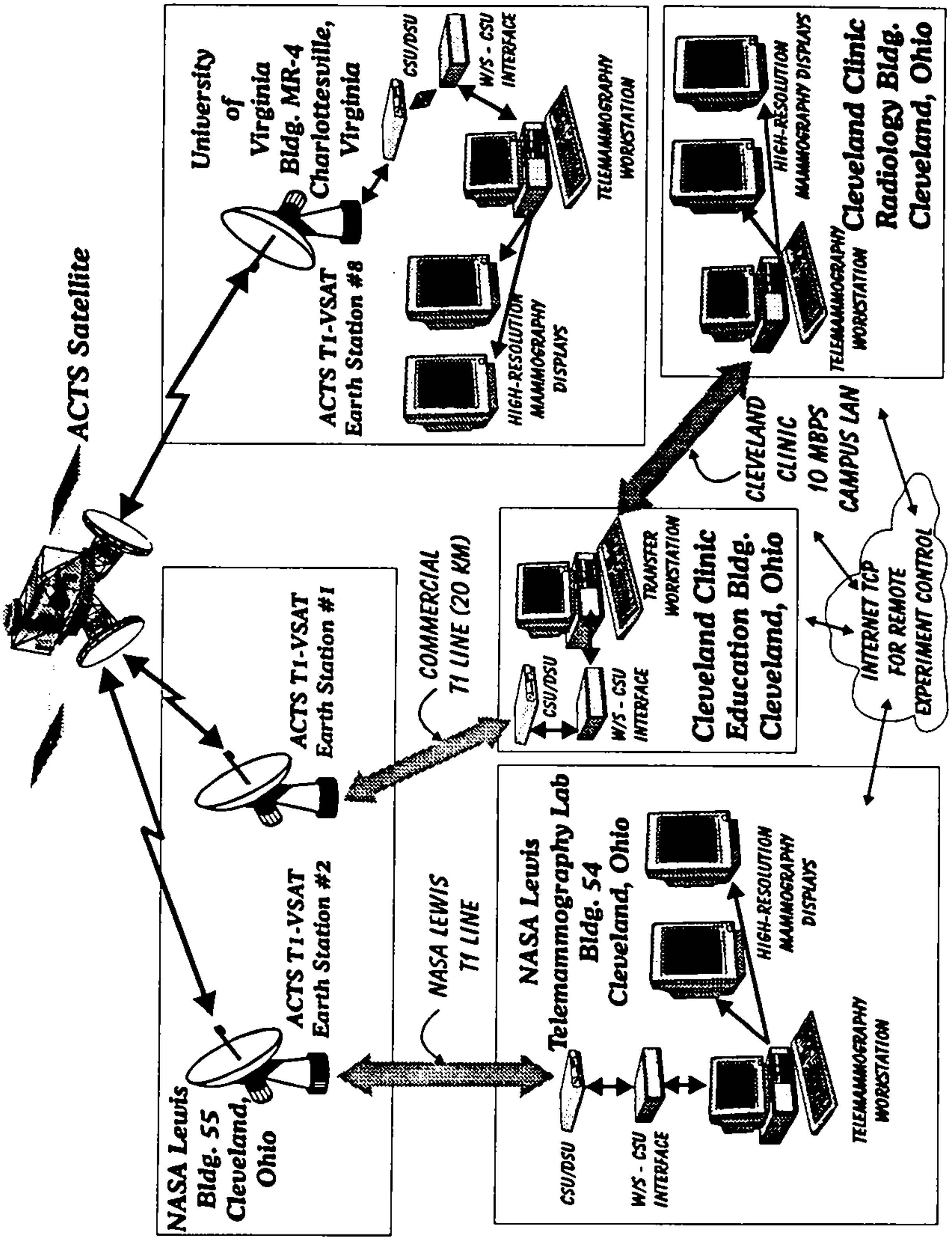


Figure 1. Configuration of the Satellite Telemammography Network Experiment

At the time of the preparation of this paper, approximately 300 images have been successfully transmitted, without error, from NASA Lewis to the Cleveland Clinic, from the Cleveland Clinic to NASA Lewis, and from NASA Lewis to the University of Virginia. These images include both uncompressed images (some over 20 Mbytes in size) as well as images compressed at several compression ratios. During this time, many attempts at image transmission have failed, but all failures have been traced to improperly configured hardware, improperly configured satellite links, terrestrial networking problems, and human error. So far, no image transmission errors have resulted from the satellite link itself.

FURTHER TECHNOLOGY ADVANCES NEEDED

So far in this paper, a number of technologies have been identified which need further development in order to enable or improve the efficiency of satellite telemammography. These include specialized telemammography workstations and software, high resolution gray scale displays, and data transmission protocols.

During the development and execution of the Satellite Telemammography Network Experiment to date, another significant technology requirement has been identified. The image compression software requires up to a minute to compress a large image, and can require several minutes to decompress the image. This significantly impacts the overall telemammography process. Faster processing of image compression algorithms, through improved workstation hardware or direct hardware implementation, is necessary.

CONCLUSION

The use of proposed new regional and global satellite networks which will offer low-cost T1-rate connectivity for telemammography promises to greatly improve the quality of life for patients for whom annual mammography screening is recommended. In particular, the ability to reach patients in rural, low population density areas far removed from centers of mammography and breast cancer expertise in a convenient and economical fashion is an exciting prospect. In addition, with over 56 million potential patients, satellite telemammography represents a potentially large market for satellite service providers.

A number of technology and clinical issues have been identified as obstructions to the viable implementation of satellite telemammography. The Satellite Telemammography Network Experiment, partnering NASA Lewis Research Center, the University of Virginia, and the Cleveland Clinic, and using NASA's ACTS Satellite, is addressing a number of these critical issues. Other issues are being addressed by the mammography and breast cancer research community. There is significant work remaining to be done before telemammography using satellite communications will become an accepted and widely used procedure. But it is hoped that the results of the Satellite Telemammography Network Experiment will serve as a catalyst for future research and development and the eventual implementation of satellite telemammography.

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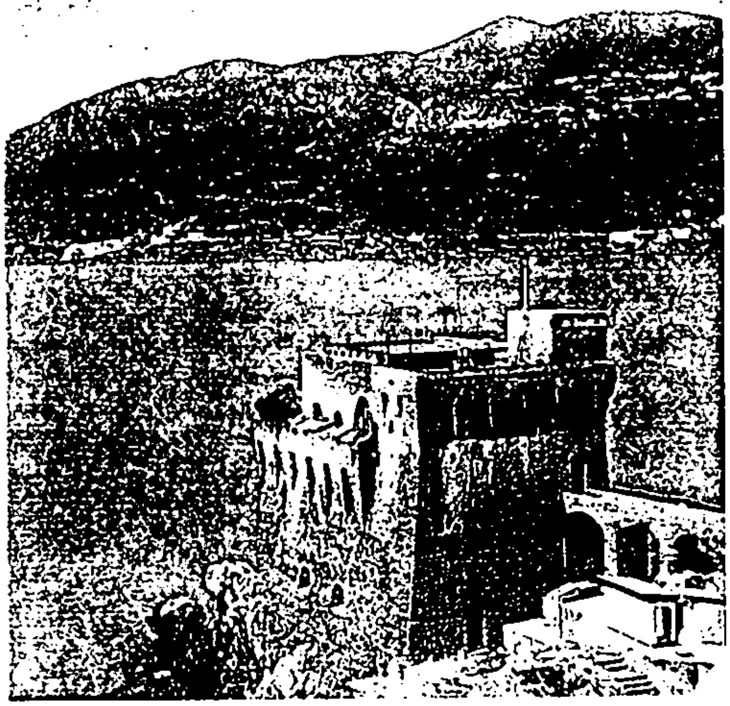

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